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Functional Specification

INNER TRIPLET QUADRUPOLE MQXA

Abstract

This specification establishes the functional requirements for the MQXA quadrupole magnets. These elements form the Q1/Q3 inner triplet optical element at interaction regions 1, 2, 5 and 8. Since the elements are identical whether installed at the low luminosity or high luminosity interaction regions, the functional requirements to the magnet design are identical for all MQXA assemblies.

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1. OVERVIEW

MQXA magnets are the quadrupole components which form the optical element Q1 and Q3 in each inner triplet of the LHC, as described in the Inner Triplet Functional Specification [1]. The MQXA is the quadrupole magnetic element, including the coils and mechanical support pieces to a perimeter defined by the outer shell of the magnet, and the end plates of each magnet. MQXA assemblies are used in the Q1 and Q3 optical elements (Figure 1).

The MQXA design and production is the responsibility of KEK. MQXB are the responsibility of Fermilab, and the corrector packages and beam position monitors are the responsibility of CERN. Fermilab is responsible for the design and assembly of the LMQX vessels, and the LQX cryostat assemblies. The beam position monitor mounting, and interconnect assembly are the responsibility of CERN.

This functional specification covers the MQXA only.

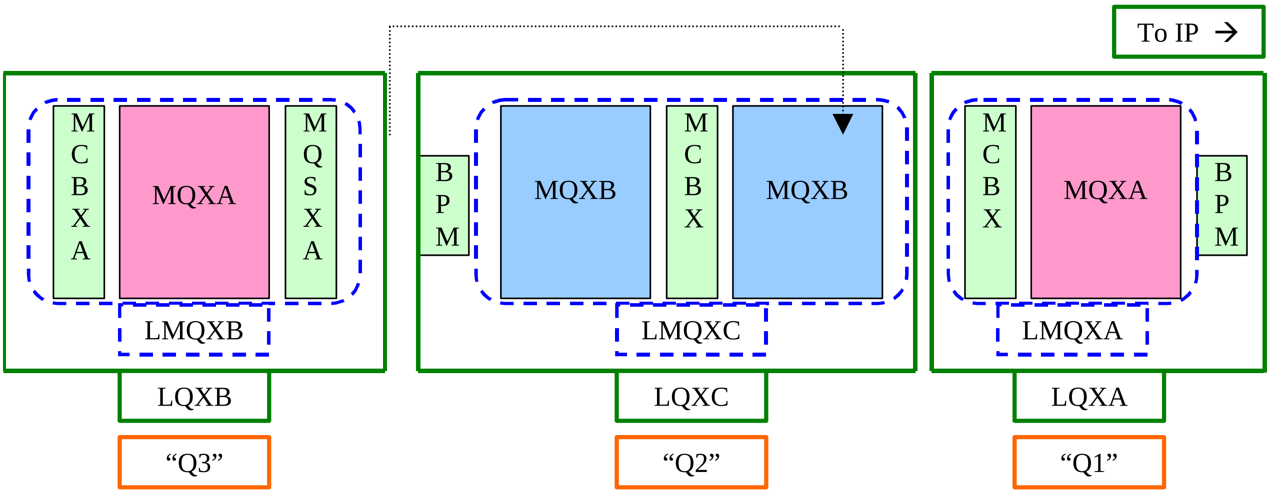

Figure 1. Inner Triplet Nomenclature.

The MQXA design (Figure 2) consists of a 4-layer Nb-Ti graded coil, which incorporates 1 wedge in each 1st and 2nd layer for field quality and which is insulated using Upilex film. G10CR material is used in the end parts. The coil package is supported in the straight section by thin stainless steel (high-Mn steel) collars and iron laminations, which are locked with three keys at each side. The two piece iron yoke provides flux return and a small amount of field augmentation. The collared coil is accurately located within the yoke. The whole assembly is surrounded by stainless steel shell. The two-part shell is welded to provide the closure of the helium vessel. The mechanical fiducial blocks are provided on the shell for the alignment measurements. A detailed description of the MQXA design can be found in [2 - 7].

The main and auxiliary bus work is routed through the cold mass in 2 slots at top and bottom. Four circular holes are provided in the yoke for thermal conduction during operation in the Helium II bath. The end plates provide attachment points for the quadrant lead splice block. Stainless steel end rings are circumferentially welded to the shell at each end of the MQXA, and provide support to the end domes and MCBX correctors which are attached during the LMQXC assembly process.

A total of 18 MQXA will be made; 16 magnets will be installed, and there will be 2 spares.

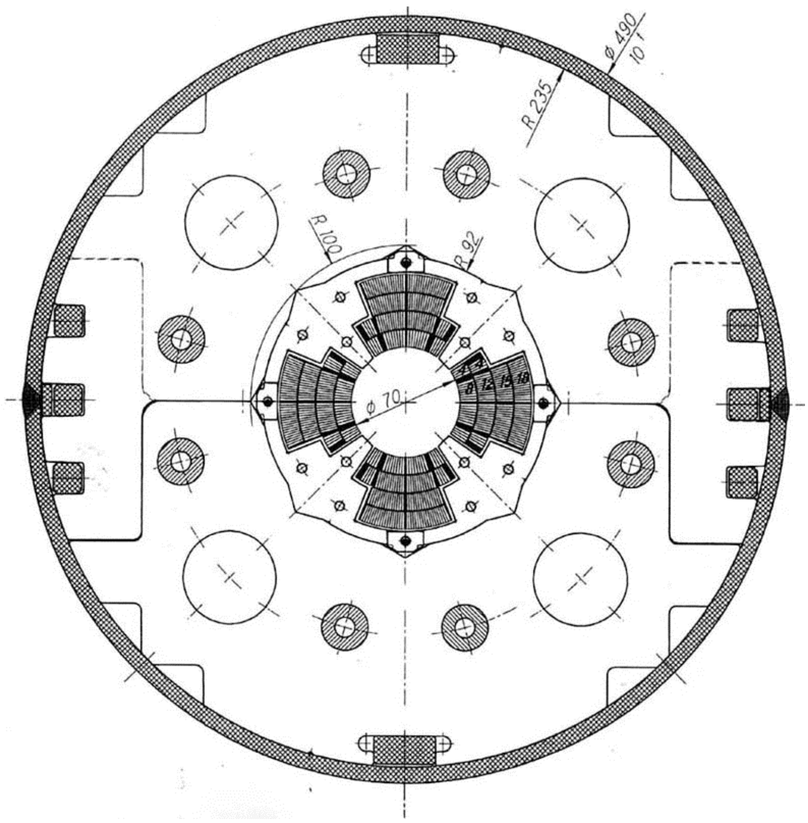

Figure 2. Cross-section through the body of the MQXA (Dimensions at room temperature).

2. MAGNETIC REQUIREMENTS

2.1 OPERATING GRADIENT

Tables 1 and 2 list operating parameters of the MQXA magnet for nominal operation in the LHC [8]. Under collision optics at nominal energy, the maximum gradient (203 T/m) is achieved at IR2 for $\beta^* = 0.5$ m. At ultimate energy, the high luminosity IRs 1 and 5 will be required to go to $\beta^* = 0.5$ m, which corresponds to a gradient of 212 T/m. The range of β^* at the low luminosity IRs 2 and 8 will be limited, as shown in Table 2, such that the gradients there will not be required to exceed the gradient at IR 1 and IR 5.

Table 1 Parameters for the MQXA Quadrupole.

Item	***Value***
Magnetic length	6.37 m*
Integral field, magnet-to-magnet variation, rms	5×10^{-4}
Operational current at 1.9K	7150 A
Operational gradient at 1.9 K	215 T/m
Inductance	~90 mH
Stored energy 215 T/m	2.3 MJ

*given by 6.389 m x 0.997 = 6.37 m (after cool-down).

Table 2 Operational b* and Gradients for the MQXA Quadrupole.

	Interaction Region		
	1, 5	***2***	***8***
Injection, E=0.45 TeV			
β* (m)	18	10	10
Gradient (T/m)	12.2	13.9	13.9
Current (kA)	~ 0.39	~ 0.44	~ 0.44
Collision, E=7.00 TeV			
β* (m)	0.5	0.5 - 50	1.0 - 50
Gradient (T/m)	197	203 – 143	202 – 162
Current (kA)	~ 6.50	~ 6.72 – 4.63	~ 6.68 – 5.29
Ultimate, E=7.54 TeV			
β* (m)	0.5	12 - 50	11 – 50
Gradient (T/m)	212	212 – 154	212 – 175
Current (kA)	~ 7.04	~ 7.04 –5.00	~ 7.04 – 5.75

Note: The Gradient given here is a little smaller than that of the gradient given for the Fermilab MQXB quadrupole, because of a slight increase in the effective length of the KEK MQXA quadrupole with respect to the original design (from 6.3 to 6.37 m),

	{MQXB (L-mag = 5.5 m}	{MQXA (L-mag=6.37 m)}
Injection Gradient	14.1 T/m	13.9 T/m
Collision, E = 7 TeV	205 T/m	203 T/m
Collision, E = 7.54 TeV	214 T/m	212 T/m.

2.2 FIELD QUALITY

The expected field quality of superconducting magnets is characterised by reference tables showing the expected mean value (<b_n> or <a_n>), uncertainty in the mean (Δb_n or Δa_n), and rms variation about the mean ($\sigma(b_n)$ or $\sigma(a_n)$) of the field harmonics. The expected distribution of harmonics for the MQXA quadrupoles is based on the measured field quality of a series of three 1 m model magnets, whose coil geometry differs from the production MQXA magnets only in length [10-11].

The reference harmonics table for the MQXA quadrupole is given in Table 3, with values presented for the magnet body at injection and collision conditions, and for the lead and the return ends [12]. The injection harmonics correspond to 0.45 TeV beam energy and field gradient ranging from 12.3 T/m to 14.1 T/m. The error tables are unchanged over the range of injection gradients with the exception of the b_6. The collision body harmonics are unchanged over the range of required gradients shown in Table 2. The end error tables are unchanged between injection and collision conditions. The field quality given by Table 3 has been used as input for tracking studies, which have demonstrated that, with the correction system specified in [1], the required dynamic aperture is achieved under collision conditions [13].

Table 3 MQXA reference harmonics v4.0. All numbers are averaged over the respective magnetic length, and expressed in units of 10^{-4} at the reference radius of 17mm. End harmonics are the same at collision and injection energies.

Body at Collision Energy (L-magnetic = 5.86 m)

n	<b>	db	σ(b)	<a>	da	σ(a)
2	10000					
3	0	0.50	0.99	0	0.50	0.99
4	0	0.67	0.54	0	0.27	0.54
5	0	0.13	0.26	0	0.13	0.26
6	+0.134	0.94	0.48	0	0.07	0.13
7	0	0.03	0.06	0	0.03	0.06
8	0	0.02	0.03	0	0.02	0.03
9	0	0.01	0.02	0	0.01	0.02
10	+0.01	0.06	0.04	0	0.01	0.01

Lead end at Collision Energy (L-magnetic = 0.31 m)

n	<b>	db	σ(b)	<a>	da	σ(a)
2	10000					
3	0	2.29	4.55	0	2.29	4.55
4	-3.52	3.13	6.26	0	0.84	1.68
5	0	0.11	1.61	0	0.11	0.21
6	4.65	0.25	0.12	0	<0.03	<0.03
7	0	<0.03	0.058	0	0.035	0.068
8	0.071	0.23	0.032	0	<0.03	0.039
9	0	<0.03	<0.03	0	<0.03	<0.03
10	-0.129	<0.03	<0.03	0	<0.03	<0.03

*note: the format has been updated to be consistent with LHC-LQX-ES-0002 (MQXB quadrupole functional specification). The integral error is given by multiplying the numbers in the table with the magnetic length (0.31 m).

Return (non-lead) end at Collision Energy (L-magnetic = 0.19 m)

N	<b>	db	σ(b)	0	da	σ(a)
2	10000					
3	0	3.73	7.42	0	3.73	7.42
4	0	5.11	10.2	0	1.37	2.74
5	0	0.18	0.36	0	0.17	0.35
6	-0.53	0.42	0.20	0	<0.05	<0.05
7	0	<0.05	<0.09	0	0.06	0.11
8	0	0.37	<0.05	0	<0.05	0.06
9	0	<0.05	<0.05	0	<0.05	<0.05
10	-0.16	<0.05	<0.05	0	<0.05	<0.05

*note: The integral error is given by multiplying the numbers by the magnetic length, 0.19 m.

2.3 FIELD AXIS

The allowable twist and straightness of the MQXA cold mass is shown in Table 4, and achievement of these values has been confirmed through measurements taken during the model magnet program [14]. The values are extracted from the IR Quadrupole Reference Alignment Table [15].

Table 4 Estimated field angle error tolerances.

Item	*Value*
MQXA twist	+/- 1 mrad /5m
MQXA straightness	+/- 0.5 mm /5m

3. ELECTRICAL REQUIREMENTS

3.1 POWER LEADS AND BUSSES

The lead end orientation of all Q3 magnets (MQXA furthest from the IP) is toward the interaction point, and that of all Q1 magnets (MQXB nearest from the IP) is away from the interaction point.

Each magnet is provided with a pair of power leads made of the same superconducting cable as used in the coils. Each lead will be marked "A" or "B" according to the standard LHC convention [16] such that, when facing the lead end of the magnet, with current entering the "A" lead and exiting the "B" lead, a quadrupole gradient with vertical field increasing to the left is produced.

3.2 QUENCH PROTECTION

During a quench the magnet should be limited to a peak “hot spot” temperature of ☐400K, and the peak voltage to ground is expected to be less than 450 V [17,18]. This is accomplished within the context of the CERN supplied power supplies, CERN supplied quench detection system and CERN supplied strip heater power supplies, through the use of voltage taps and quench protection strip heaters.

The magnet will have voltage taps located on each magnet lead and at the electrical midpoint of the magnet circuit. This configuration allows quenches to be detected via a voltage imbalance between half magnet coil circuits. There are four strip heaters per magnet, with each heater covering approximately 12 turns of two azimuthally adjacent outer coils. The four heaters are wired into two independent circuits. Each circuit will quench all four quadrants and provides full magnet protection.

Once a quench is detected in any element in the inner triplet, the power supply system will be turned off and all quench protection strip circuits in all magnets in the triplet will be energised.

3.3 INSTRUMENTATION

For quench protection, two voltage taps will be provided at each of the two magnet leads and the centre point of the coil. Each quench heater circuit will have two wires, giving a total of four per magnet. The wires will be insulated with polyimide, according to the recommendations in [19].

The rectangular bus slots, as shown in Figure 2, that are not otherwise allocated for bus work, will be used for routing instrumentation wires. Wires for the Q2 magnet as well as feed-throughs from the Q1 magnet pass through Q3, and include voltage taps and quench protection heaters leads and cryogenic instrumentation leads.

3.4 VOLTAGE LIMITS

All components are designed to withstand the maximum voltages that can appear during normal operation, including ramping up, ramping down and quenching. The magnet coils and the quench protection heaters will be tested at 1.5 kV in gaseous helium at 1 atm pressure prior to the cold test. This value is based on the estimated peak voltages to ground [17,18] occurring during magnet operation in liquid helium, summarised in Table 5, and on the test specifications in [20]. Prior to cryogenic operation, additional hi-pot tests will be performed in room temperature nitrogen gas to assure that the magnets meet these specifications.

Table 5 Required hi-pot test voltages in liquid helium at 1 atm pressure prior to installation in the machine.

Circuit Element	V_{max}	$V_{hi\text{-}pot}$
Quench Protection Heaters	450 V	1400 V
Magnet Coil	450 V	1400 V

4. CRYOGENIC REQUIREMENTS

All MQXA magnets operate in 1.9K superfluid helium bath. The magnets are designed for 20 bar maximum internal pressure, and are pneumatically pressure tested to 125% of that value during acceptance tests.

5. RADIATION REQUIREMENTS

The inner triplets of the LHC are subjected to extremely high radiation loads due to secondaries from the pp-interactions, particularly at the high luminosity interaction points 1 and 5. The actual dose rate depends on the location of the magnet, and varies strongly within the individual magnet in both azimuth and longitudinal position. The maximum dose rate along the inner triplet in IP 1 and 5 is at 43 m from the interaction point at the coil mid-plane. Table 6 summarises the peak yearly-integrated dose expected [21] to be deposited in the G10CR inner coil end parts, which are the most radiation vulnerable components, the inner coil straight section, where the dose is maximum, and at the outer radius of the vacuum vessel for the LQXC. The peak dose rates in the coil and end parts are averaged over 20 degrees in azimuth. The annual dose is calculated assuming that the LHC operates for 200 days per year at an average luminosity which is 50% of the nominal luminosity of $1x10^{34}\ cm^{-2}sec^{-1}$.

The material limitations are taken from [22]. The least radiation tolerant material used in the magnet is G10CR, which is used in the coil end parts. The radiation lifetime of the MQXA quadrupole is expected to be limited by the end part material, whose mechanical properties are degraded by 50% after an integrated dose of approximately 20 MGy. At the dose rate given in Table 6, this corresponds to approximately 7 years radiation lifetime.

Table 6 Expected yearly radiation dose at nominal luminosity in IP1/5 as a function of radial location.

Radial Location	*Interaction Region*	*Dose, MGy/yr*
Inner coil straight section	IR1/5	3.9
Inner coil end parts	IR1/5	3.4
Vacuum Vessel	IR1/5	0.006

6. RELIABILITY REQUIREMENTS

6.1 LIFETIME

The quadrupoles are expected to survive 7 years of LHC operation under nominal luminosity conditions, limited primarily by the integrated radiation dose to the materials in the coils. To extend the useful life of the magnets beyond this, the inner triplet assemblies may be interchanged between the low luminosity and high luminosity IPs. The number of thermal cycles, powering cycles, and quenches required over the expected lifetime of the LHC machine are shown in Table 7.

Table 7 Required lifetime parameters.

Item	*Value*
Number of Thermal Cycles	25
Number of Powering Cycles	12,000
Number of Quenches	10

6.2 SPARES

Two fully cold-tested MQXA magnets will be delivered as spares. The spares will allow to be installed in any location.

7. CERN PROVIDED PARTS

CERN has agreed to provide the following components to be installed in the MQXA, as listed in Table 8. These will be provided for the two full-scale prototype MQXA as well as for the production magnets.

Table 8 CERN provided parts.

Item	*Quantity*
Quench Protection Heaters	84
Cables for QPHTS (Gauge 20)	~ 1000 m
Cables for voltage taps (Gauge 26)	~ 1000 m

8. LIST OF INTERFACES

All interfaces of the MQXA cold mass assembly are to other components in the LMQXA, the helium vessel and the LQXC cryostat. The details of these interfaces are contained in the separate document listed in Table 9.

Table 9 MQXB Interface Specification.

Specification	*Interfaces*
MQXA to Cryostat Interface Specification	End domes Bore tube Support Ring

9. REFERENCES

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